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Search for Evidence of Two-Photon Exchange: Measurement of the Recoil Vector Polarizations in Elastic Electron-Hadron Scattering

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Abstract

We propose to measure the proton and deuteron vector polarizations in elastic electron scattering using Hall A Focal Plane Polarimeter. With unpolarized electron beam, we will measure the proton and deuteron induced vector polarization component P_y. This component is identical to zero in the one-photon exchange formalism due to time reversal invariance. The appearance of such *T-odd* polarization observable is an indication of the presence of a two-photon exchange contribution to elastic electron-hadron scattering. With a polarized electron beam, we will also measure the deuteron transferred vector polarization components P_x and P_z. These are the same two components measured in the extraction of G_E^p [1] from the reaction $\vec{e}p \to e'\vec{p}$.

1 Introduction

In this letter of intent, we outline a program to measure the recoil vector polarizations in *ed* and *ep* elastic scattering. The program includes the following elements:

- We intend to measure the induced polarization in *ep* elastic scattering. This polarization results from two-photon exchange, and an observation of a non-vanishing polarization might help to explain the observed difference between proton form factors extracted with recoil polarization techniques and with Rosenbluth separations.

- We intend to measure the induced polarization in *ed* elastic scattering. The physics motivation is the same as in the *ep* elastic scattering case. Due to the sharper fall off of the deuteron elastic form factors, the induced polarization would be expected to be larger and easier to observe. However, the *ed* induced polarization cannot be directly tied to that in *ep* elastic scattering.

- We intend to simultaneously measure the vector polarization transfer ratio P_x/P_z in *ed* elastic scattering. The polarization transfer yields a ratio of form factors, $(G_C + \frac{1}{3}\eta G_Q)/G_M$. The technique has been known for about 20 years, but no measurements have ever been performed. The experimental considerations are similar to those for *ep* elastic scattering. These data will be provide independent check on the extracted deuteron form factors - other than a few 180° measurements, the form factors rely on Rosenbluth separations with only a few ϵ points.

2 Motivation – *ed* Elastic Scattering

The role of two-photon exchange in electron-hadron (*eh*) scattering was recently revisited in Refs. [2] and [3]. The study of the structure of hadrons and nuclei with electromagnetic probes is based on the validity of the one-photon mechanism for elastic and inelastic electron-hadron scattering. On the basis of a well established formalism, the measured cross sections and polarization observables can be directly related to the electromagnetic form factors and structure functions. The validity of this approach is based on the assumption that the possible two-photon contribution, where the momentum transfer is shared between two *hard* photons, is small. The relative contribution of the two-photon exchange would be of the order of the fine structure constant $\alpha \simeq 1/137$. However, several calculations [4] showed that the simple rule of α counting for the estimation of the relative role of the two-photon contribution to the amplitude of elastic *ed* scattering may not hold at large momentum transfer. This effect should be particularly prominent in *ed* elastic scattering, due to the steep decrease of the deuteron form factors and it would manifest already at momentum transfer of the order of 1 $(\mathrm{GeV/c})^2$, in particular in the region of diffractive minima. The standard calculations of radiative corrections for *eh* scattering contain the contribution of two-photon exchange where most of the transferred momentum is carried by one photon, while the other photon has very small momentum.

Experiments completed up until now [5] have not shown any deviation from the one-photon expectation. However, the two-photon contribution has been recently experimentally observed in the range of very small energies in atomic physics [6] and in the experiments on *ed* elastic scattering, no test of the validity of the one-photon mechanism, like the Rosenbluth separation, was done and no vector polarization measurement exists in this range of momentum transfer.

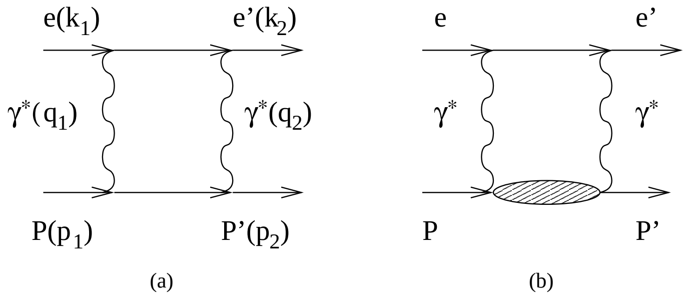

Figure 1: Two-photon exchange mechanism responsible for single–spin asymmetries in elastic *ep*–scattering [3]. a) Elastic intermediate state. b) Inelastic intermediate states.

3 Motivation – *ep* Elastic Scattering

The induced polarization is in general related to the absorptive, non-forward part of the off-shell Compton amplitude, $\gamma^* p \to \gamma^* p$ scattering. At large momentum transfers, perhaps starting from Q^2 above 1 or 2 (GeV/c)^2, the mechanism can be described by the zeroth moment of generalized parton distributions. Calculations [3] indicate that the induced polarization is likely to be a few percent, and to grow with energy. Such measurements could thus become an important part of efforts to characterize the soft structure of the nucleon at Jefferson Lab.

Our particular motivation here are the potential theoretical reasons why Rosenbluth separations and the recoil polarization technique can give different answers for the proton form factors. The two-photon exchange radiative correction is shown in Fig. 1. The off-shell intermediate state proton can lead to an ϵ-dependent correction that distorts the form factors extracted in a Rosenbluth separation. The correction is likely to be at most a few percent to the cross section, but it is model dependent and not under control. The correction applies also to the form factors extracted with the recoil polarization technique, but here it is likely to be at most a few percent to the form factor ratio extracted – it is believed to affect the two transfer polarization coefficients similarly, and thus to not affect the ratio much.

Thus, given the difference observed to date between the Rosenbluth and recoil polarization techniques, a measurement that is directly related to the two photon exchange is desirable.[1] The measurement to be performed is of the induced polarization, P_y, in elastic *ep* scattering. This observable vanishes in one photon exchange; in *ep* elastic scattering it arises entirely from two photon exchange. Measurements of P_y thus provide a constraint on the treatment of the intermediate state off-shell proton. Even limits of about ± 0.01 would be significant for understanding the corrections.

[1]We note that as of this writing, there are not even preliminary data for the modified Rosenbluth measurement, E01-001, in Hall A. The agreement of these data with other Rosenbluth separations would make this aspect of the proposal motivation much more compelling.

4 Elastic Electron Deuteron Scattering

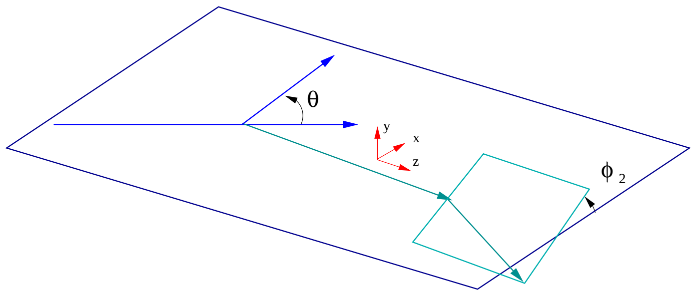

Figure 2: Definition of electron scattering, recoil particle, and second scattering coordinate systems. The recoil coordinate xz are in the electron scattering plane.

The following general formula holds for the differential cross section of elastic scattering of an unpolarized electron by an unpolarized, non-zero spin, target:

$$\frac{d\sigma}{d\Omega} = \left.\frac{d\sigma}{d\Omega}\right|_{NS} \left[A(Q^2) + B(Q^2)\tan^2(\theta/2)\right] = \left.\frac{d\sigma}{d\Omega}\right|_{NS} S(Q^2,\theta)\,, \tag{1}$$

where $S(Q^2,\theta)$ is defined by this relation, and

$$\left.\frac{d\sigma}{d\Omega}\right|_{NS} = \frac{\alpha^2 E' \cos^2(\theta/2)}{4E^3 \sin^4(\theta/2)} = \sigma_M \frac{E'}{E} = \sigma_M \left(1 + \frac{2E}{M_d}\sin^2 \tfrac{1}{2}\theta\right)^{-1}\,, \tag{2}$$

is the cross section for scattering from a particle without internal structure (σ_M is the Mott cross section). For spin-1 particles like the deuteron, the structure functions A and B depend on the three electromagnetic form factors (shown in Fig. 3):

$$\begin{aligned} A(Q^2) \quad &= G_C^2(Q^2) + \frac{8}{9}\eta^2 G_Q^2(Q^2) + \frac{2}{3}\eta G_M^2(Q^2) \\ B(Q^2) \quad &= \frac{4}{3}\eta(1+\eta) G_M^2(Q^2)\,, \end{aligned} \tag{3}$$

with $\eta = Q^2/4M_d^2$.

While cross section measurements can determine A, B, and G_M, separating the charge G_C and quadrupole G_Q form factors requires polarization measurements. The polarization of the outgoing deuteron can be measured in a second, analyzing scattering. The cross section for the double scattering process can be written as [7]:

$$\begin{aligned} \frac{d\sigma}{d\Omega d\Omega_2} = \left.\frac{d\sigma}{d\Omega d\Omega_2}\right|_0 \Big[1 \quad &+ \tfrac{3}{2} h\, P_x A_y \sin\phi_2 \\ &+ \tfrac{1}{\sqrt{2}} t_{20} A_{zz} - \tfrac{2}{\sqrt{3}} t_{21} A_{xz}\cos\phi_2 + \tfrac{1}{\sqrt{3}} t_{22}(A_{xx} - A_{yy})\cos 2\phi_2\Big]\,, \end{aligned} \tag{4}$$

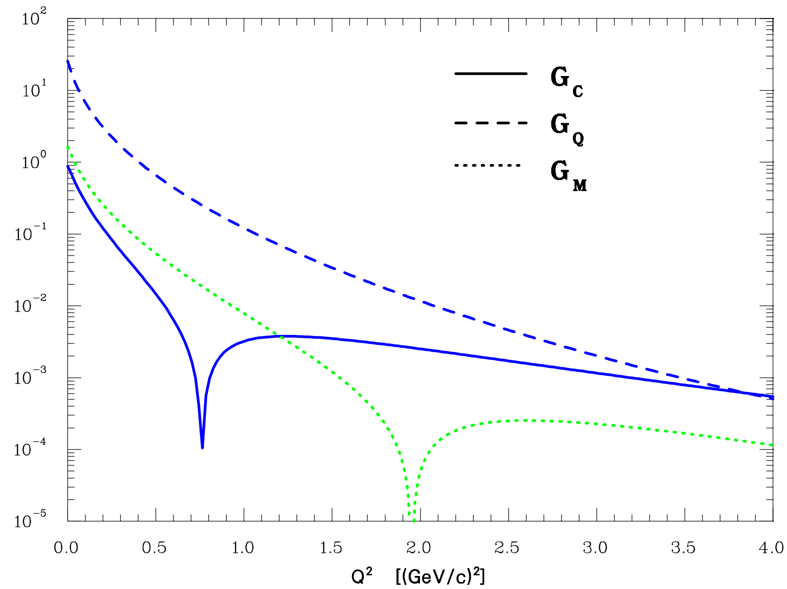

Figure 3: The deuteron electromagnetic form factors: G_C, G_Q, and G_M.

where $h = \pm 1/2$ is the polarization of the incoming electron beam, ϕ_2 the angle between the two scattering planes (defined in Fig. 2), and A_y and the A_{ij} are the vector and tensor analyzing powers of the second scattering. We give P_z below even though it does not enter the cross section of Eq. (4) directly. When the deuteron passes through the spectrometer between the first and the second scattering, it causes the polarizations to precess. Then in order to calculate the vector polarization components of the deuteron when it enters the second reaction, both P_x and P_z of the deuteron as it emerges from the first reaction must be known.

The polarization quantities P_i and t_{2m_ℓ} (shown in Fig. 4 for $\theta_e = 140.0°$) are functions of the form factors and the electron scattering angle:

$$
\begin{aligned}
S\,P_x &= -\tfrac{4}{3}\left[\eta(1+\eta)\right]^{1/2} G_M (G_C + 9\tfrac{1}{3}\eta G_Q)\ \tan\tfrac{1}{2}\theta \\
S\,P_z &= \ \ \tfrac{2}{3}\eta\left[(1+\eta)(1+\eta\sin^2\tfrac{1}{2}\theta)\right]^{1/2} G_M^2 \tan\tfrac{1}{2}\theta\ \sec\tfrac{1}{2}\theta \\
-\sqrt{2}S\,t_{20} &= \tfrac{8}{3}\,\eta\, G_C G_Q + \tfrac{8}{9}\,\eta^2 G_Q^2 + \tfrac{1}{3}\eta\left[1 + 2(1+\eta)\tan^2\tfrac{1}{2}\theta\right] G_M^2 \\
\sqrt{3}\,S\,t_{21} &= 2\,\eta\left[\eta + \eta^2\sin^2\tfrac{1}{2}\theta\right]^{1/2} G_M G_Q\ \sec\tfrac{1}{2}\theta \\
-\sqrt{3}S\,t_{22} &= \tfrac{1}{2}\,\eta\, G_M^2\,.
\end{aligned}
\tag{5}
$$

The same combinations of form factors occur in the tensor polarized target asymmetry as in the recoil deuteron tensor polarization.

If the electron beam is not polarized, parity invariance could be used to show that $P_x = P_z = 0$. In general P_y is not zero. It is not forbidden by parity or any other invari-

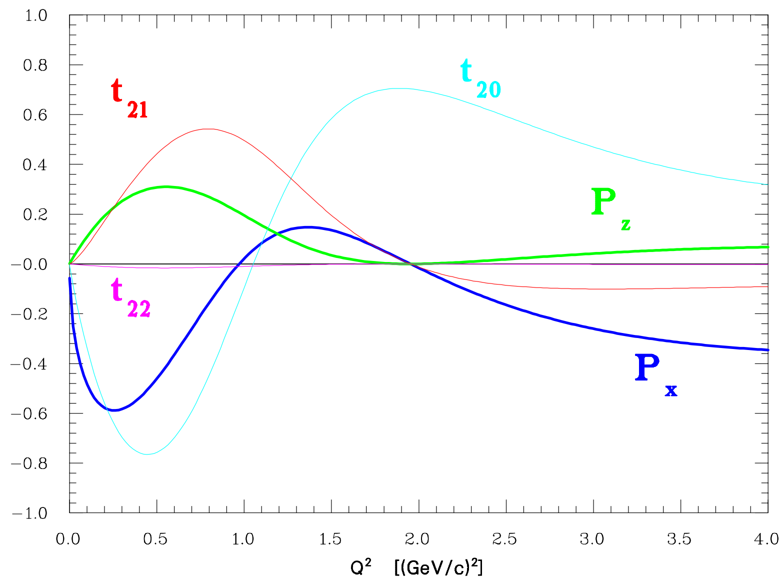

Figure 4: Recoil deuteron polarization components P_x and P_z at electron scattering angle $\theta_e = 140.0°$ versus Q^2. Also shown the deuteron tensor polarization components.

ance principle. That $P_y = 0$ is a consequence of making the usual one-photon exchange approximation. Also with the one-photon exchange approximation the tensor polarizations are independent of the electron polarization. Hence only the tensor polarizations which would be present if the electron was not polarized (*i.e.*, those tensor polarizations allowed by parity invariance, are nonzero).

5 Experimental Techniques

5.1 Focal Plane Polarimeter

This experiment will detect the scattered electron in coincidence with the recoil deuteron. The scattered electron will be detected in BigBite spectrometer at the angle 140°. The deuteron polarization will be measured with the Focal Plane Polarimeter (FPP) of Hall A using carbon analyzer. In principle, any proton polarimeter may be used as a vector deuteron polarimeter.

Measurements of recoil proton polarization have now been performed in about 10 experiments in Jefferson Lab Hall A. The technique is standard and will not generally be discussed here, except for a discussion of the false asymmetries. Only deuteron tensor polarizations have been measured previously at Jefferson Lab, so we concentrate our discussion on this aspect of the experiment.

The vector analyzing power for d-carbon scattering has a typical value of 0.3 with polarimeter efficiency of 0.1 [8]. Since, in the inclusive d-carbon reaction, two of the three tensor analyzing powers T_{20} and T_{21} are very close to zero (see Refs. [9], [10], [11], and [12]), the FPP will be mainly a vector polarimeter. The third tensor analyzing power T_{22} is approximately equal to 0.1. This is important since the T_{21} leads to a $\cos\phi_2$ modulation, similar to the signal of P_y. The T_{22} modulation, $\cos 2\phi_2$, does not affect the extraction of the vector polarizations. Further, the helicity dependence allows a clean separation of the induced and transferred polarizations.

Because $\mu - 1$ is small for the deuteron, compared to the proton, there is relatively little difference in the spin precession between the different proposed kinematics. The induced polarization is reduced by about 20%. The z-component of transfered polarization is rotated to be about 60% transverse in the focal plane.

5.2 Measuring P_y in the Reaction $ep \to e'\vec{p}$

In principle measurements of P_y could have been done along with the polarization transfer measurements of [1]. However, the induced polarization is technically very different from the polarization transfer measurements. The induced polarization requires a very careful control of polarimeter systematics, especially the alignment and false asymmetries. For most Jefferson Lab experiments in the past, we have *assumed* that the induced polarization of the ep protons vanishes; the ep protons summed over helicity states are then used to confirm the alignment of the polarimeter. The polarization transfer measurements are extremely *insensitive* to issues of alignment and false asymmetries, which cancel in the difference between the helicity states - see, e.g., [14]. Doing the induced polarization measurement in these experiments was not justified due to the additional calibration time required. Thus, while uncertainties on the polarization transfer observables had statistical uncertainties about $\pm$ 0.001, the systematic uncertainty on the induced polarization was far in excess of $\pm$ 0.01.

Here, we propose a new technique for determining the false asymmetries of the polarimeter. As has been our practice in the past, the polarimeter will be initially aligned by a combination of cosmic ray data and straight-through data, taken with the analyzer removed. After the chambers are initially aligned to the VDCs, the inter-chamber alignment is enhanced by using a carbon diffuser after the VDCs to scatter particles into a larger phase space within the focal plane, to enhance the alignment.

The novel feature here is that we propose to check the false asymmetries with the $ep \to e'\pi^+n$ reaction. The use of a coincidence measurement, while not strictly necessary, will ensure a clean sample of π^+. This reaction has the benefit that large π^+ rates are possible, and there are no spin effects from the spin-0 pion. The pd total cross sections for few GeV/c momenta are typically about 90 mb, and largely inelastic. The πd total cross sections for 1 – 2 GeV/c momenta are similar, about 60 – 80 mb, and largely inelastic. Thus there will be similar absorption effects for protons and pions in the analyzer. Note that differential absorption depending on scattering angle is not an issue for particles normally incident on the face of the analyzer. To optimize uncertainties, the π^+ calibrations need to be run for statistics about equal to those of the ep measurements.[2]

[2]However, as long as chamber positions do not depend on the analyzer thickness, it is only necessary

They will also provide the necessary false asymmetry data for the *ed* induced polarizations.

From the calculations of [3], the induced polarization should be maximal near $\theta_{\text{c.m.}} = 90°$. Table 1 shows possible data points. Since this is an initial exploratory measurement, the kinematics are flexible, though large changes in momentum transfer would require much different beam times.[3]

E_e (GeV)	Q^2 $(\text{GeV/c})^2$	$\theta_e \approx \theta_p$ (deg.)	Rate Hz	Time days
0.8	0.4	49	2000	0.5
1.6	1.0	45	2000	0.5
2.4	1.6	38	1500	1.0
3.2	2.3	35	500	2.0
4.0	3.0	33	200	5.0

Table 1: Possible kinematics, rates, and time for elastic *ep* induced polarization measurement.

E_e (GeV)	Q^2 $(\text{GeV/c})^2$	ω (GeV)	θ_e (deg.)	θ_d (deg.)	Time days	ΔP_y (abs)	ΔR (%)
0.8	0.45	0.12	54	54	1.0	0.004	5
0.8	0.70	0.19	74	43	4.0	0.01	12
1.6	1.00	0.27	40	56	4.0	0.01	5

Table 2: Possible kinematics, rates, and time for elastic *ed* induced polarization measurement near $90^\circ_{\text{c.m.}}$. These estimates indicate the importance of running in optimal kinematics, and the limited range of Q^2 available for *ed* elastic scattering measurements, due to the sharp drop in the form factor and the resulting decrease in count rate with Q^2. These induced polarization measurements would also provide 5 - 12% uncertainties on the form factor ratio of Eq. 6.

to make a single measurement of $ep \to e'\pi^+ n$, not one for every analyzer setting. Too, it is not necessary to perform these measurements at the same momentum as the measured protons or deuterons.

[3]A benefit of the recoil polarization technique, as opposed to measuring polarized target asymmetries, is that recoil polarizations can be measured with installed equipment, and there is no need for more than a few days of set up time for the experiment to be able to run. The the two techniques have similar figures of merit, as recoil polarimetry operates at $\approx 10^4$ times greater luminosity, but also requires nearly $\approx 10^4$ times greater counts. Both techniques require that potential false asymmetries be kept under control.

5.3 Measuring P_y in the Reaction $ed \to e'\vec{d}$

Using unpolarized electron beam, we will measure the deuteron induced vector polarization component P_y. This component is identical to zero in the one-photon exchange formalism due to T invariance. The coefficient multiplying this quantity must also be odd if it is to be non-zero. Since T invariance involves a complex conjugation, the imaginary part of the two-photon exchange will be odd under T, and its interference with the real one-photon exchange will be the amplitude that could be detected by a P_y measurement. Thus, the appearance of this polarization observable is an indication of the presence of T-*odd* contribution to ed elastic scattering from two-photon exchange.

Only one experiment has measured the recoil vector deuteron polarization P_y, in *unpolarized* ed elastic scattering at $Q^2 = 0.5$ (GeV/c)^2 [13]. The experiment was motivated at the time as a test of time-reversal invariance. The value obtained for the vector polarization was $P_y = 0.0756 \pm 0.088$, consistent with 0.

5.4 Measuring P_x and P_z in the Reaction $\vec{e}d \to e'\vec{d}$

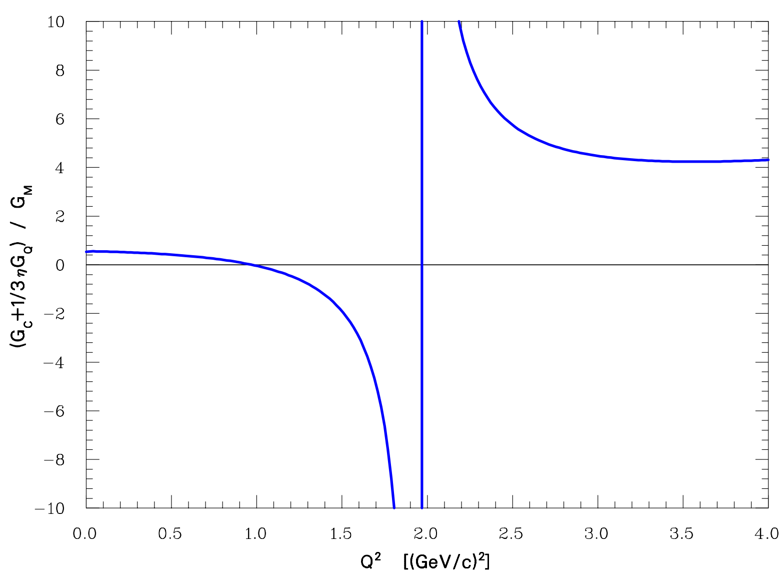

Figure 5: The ratio $(G_C + \frac{1}{3}\eta G_Q)/G_M$ versus Q^2.

Using polarized electron beam, we will measure the deuteron transferred vector polarization components P_x and P_z. These are the same two components measured in the extraction of G_E^p when using proton target. The ratio $(G_C + \frac{1}{3}\eta G_Q)/G_M$ (shown in Fig. 5) can then be obtained directly from:

$$R \equiv (G_C + \frac{1}{3}\eta G_Q)/G_M = -\frac{1}{2}\Big[\eta(1+\eta\sin^2\tfrac{1}{2}\theta)\Big]^{1/2} \sec\tfrac{1}{2}\theta \;\; \frac{P_x}{P_z}\,. \tag{6}$$

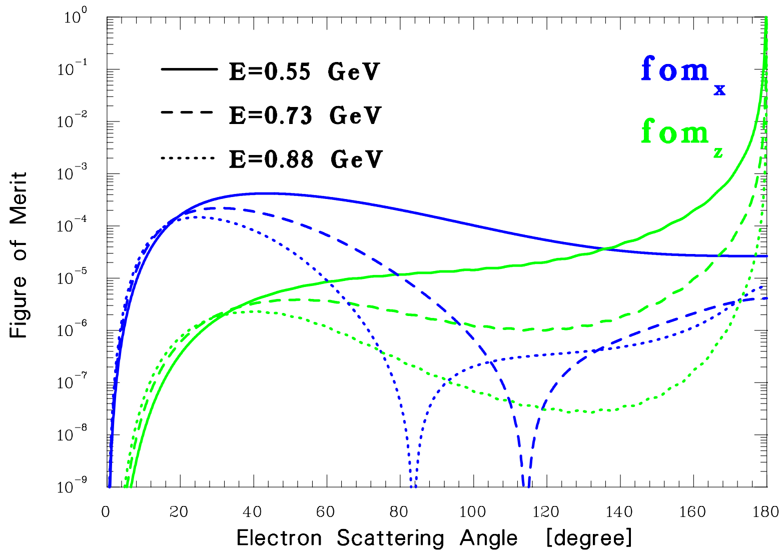

Figure 6: Figure of merit as a function of the electron scattering angle for three different beam energies. The figure of merit is defined as: $\mathrm{fom}_x = S\,P_x^2$ and $\mathrm{fom}_z = S\,P_z^2$.

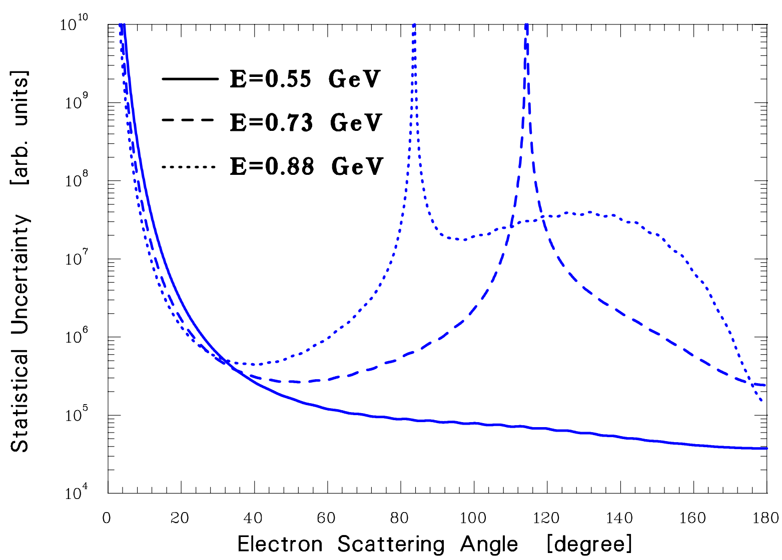

Figure 7: Optimizing the kinematics for measuring $\frac{P_x}{P_z}$. The optimal kinematics is at the minimum of $\frac{1}{S}(\frac{1}{P_x^2} + \frac{1}{P_z^2})$.

Preliminary figure of merit and a first attempt to optimize the kinematics are shown in Figs. 6 and 7. Polarized electron beam of 100 μA with 80% polarization will be scattered off 15 cm LD_2 target. The proposed kinematics are listed in Table 3.

E_e GeV	Q^2 $(GeV/c)^2$	E' GeV	θ_e deg.	T_d GeV	P_d GeV/c	θ_d deg.	Rate Hz	P_x	P_z	A_y	eff.	Time days
0.55	0.7	0.36	140.0	0.19	0.86	15.7	10	-0.3	0.3	0.3	0.1	0.5
0.73	1.1	0.43	140.0	0.30	1.10	14.7	1	0.0	0.2	0.3	0.1	3.0
0.88	1.5	0.48	140.0	0.40	1.29	13.9	0.1	0.1	0.0	0.3	0.1	25.0

Table 3: Proposed kinematics and expected rates. Listed is the time needed to collect 200k events which would give $\Delta P = 0.03$ statistical uncertainty.

6 Acknowledgment

We acknowledge very stimulating discussions with Franz Gross and Andrei Afanasev.

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